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SLAB AVALANCHE RELEASE AREA ESTIMATION: A NEW GIS TOOL

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ABSTRACT: Location and extent of avalanche starting zones are of crucial importance to correctly estimate the potential danger that avalanches pose to roads, railways or other infrastructure. Presently, release area assessment is based on terrain analysis combined with expert judgment. Tools for the automatic definition of release areas are scarce and exclusively based on parameters derived from summer topography, such as slope and curvature. This leads to several limitations concerning the performance of such algorithms. Foremost, they neglect the smoothing effect of the snow cover on terrain morphology. Winter terrain often considerably deviates from its underlying summer terrain, thus changing potential release area size and location of surface slab avalanches. Hence, we present a new GIS based tool which estimates potential release areas by association of traditional contributory variables, such as slope and forest cover with variables particularly related to snow cover influence on topography. We introduce a scale dependent roughness parameter and a wind shelter parameter accounting for varying winter topography and snow deposition patterns with increasing snow depth. Further, uncertainty in the definition of the parameters is accounted for by using a fuzzy logic classification approach. This approach is especially useful for defining release area scenarios e.g. depending on snow depth, which is not possible with existing tools.

KEYWORDS: release area, slab avalanche, hazard mapping, risk management, fuzzy logic

1. INTRODUCTION

Location and extent of avalanche starting zones are of crucial importance to correctly estimate the potential danger that avalanches pose to roads, railways or infrastructure. Presently, release area assessment is based on terrain analysis combined with expert judgment. Tools for release area modeling are scarce and exclusively based on parameters derived from summer topography, such as slope and curvature (e.g. Maggioni and Gruber, 2003; Bühler et al., 2013). Further, many algorithms are calibrated to work with coarse resolution digital elevation models (around 25 m). They only capture macrotopography (ridges, valleys), but omit microtopographical features such as varying surface roughness or gullies. This implies several limitations concerning the performance of such algorithms.

Whereas microtopography is negligible in extreme situations, it is highly relevant for smaller, more frequent avalanches, which cause the vast majority

of casualties in Switzerland today and threat mountain transport ways and ski runs. Small-scale terrain features delineate release areas with shorter return period, where only parts of the whole potential starting zone release. At the same time, snow accumulation smoothes out microtopography, reducing snowpack variability in the surface layers (Mott et al., 2010) and the mechanical support of a slab (McClung and Schaerer, 2002). The smoothing effect of snow distribution on terrain morphology is so far neglected by current release area algorithms. Therefore, it seems very likely that release area calculations performed on a summer terrain may strongly differ from calculations on a more realistic winter terrain.

We present a new GIS based tool which estimates potential release areas by association of traditional contributory variables, such as slope and forest cover with variables particularly related to snow cover influence on topography. We introduce a scale dependent roughness parameter and a wind shelter parameter accounting for varying winter topography and snow deposition patterns with increasing snow depth. Further, uncertainty in the definition of the parameters is accounted for by using a fuzzy logic classification approach.

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2. FUZZY LOGIC MODELING OF TERRAIN VARIABLES

The design of current release area algorithms is mainly rule – based, considering expert knowledge and past studies of topographical parameters of avalanche release areas. Due to the complexity of avalanche formation, it is very difficult to define precise rules and expert decision making still contains a significant amount of uncertainty. To deal with such imprecise data or diffuse rules, Zadeh (1965) introduced the fuzzy logic concept. This approach overcomes the concept of sharp (so called crisp) thresholds by introducing the membership concept. Every element, instead of belonging to a class (or not), is attributed a degree of membership belonging to that class (called set in fuzzy set theory). This concept is very appealing for natural hazards applications as it allows integrating human reasoning capabilities into knowledge based expert systems. It has already been successfully applied to Landslide Susceptibility Mapping (e.g. Schernthanner, 2007) and risk modelling of wet snow avalanches (Zischg et al., 2005).

The mathematical formulation of a fuzzy set as initially defined by Zadeh, 1965 is: "Let X be a space of points (objects), with a generic element of X denoted by x . Thus, $X = \{x\}$. A fuzzy set (class) A in X is characterized by a membership (characteristic) function $f_A(x)$ which associates with each point in X a real number in the interval $[0,1]$, with the value of $f_A(x)$ at x representing the "grade of membership" of x in A ".

Generally, simple and computationally efficient membership functions are favored in fuzzy logic implementations. Very simple implementations are for example triangular or trapezoidal functions. Due to their computational efficiency they are often used in real time applications where calculation speed is critical. However they only consist of linear segments and introduce very sharp changes at the corner points. To overcome these drawbacks, generalized bell (also referred as Cauchy membership function) or Gaussian functions are used (Jang et al., 1997). They are characterized by smooth outlines where the sharpness of transition can be set by a parameter. We found bell shaped functions defined by

$$\mu(x) = 1/(1 + ((x - c)/a)^{2b}) \quad (1)$$

well suited and applied them for modeling of terrain parameters for potential release area (PRA) definition.

2.1 *Slope*

One of the most relevant terrain variables is slope (Schweizer et al., 2003). Slope maps are regularly consulted in current avalanche hazard mapping practice as a basis for release area assessment.

Slope values between 28° and 60° are considered to be potential release areas. The degree of membership $\mu(x)$ to the class PRA of slope is modeled using a generalized bell membership function with the parameters $a = 8$, $b = 3$ and $c = 40$ (Fig. 1).

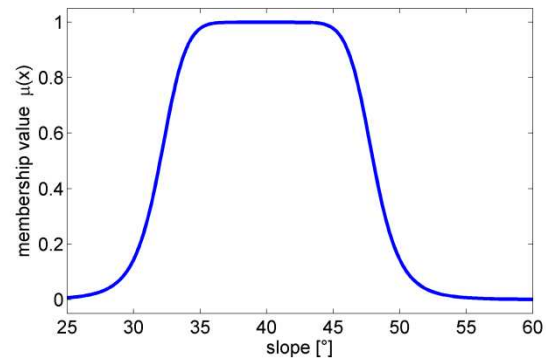


Fig. 1: Membership function for slope

This function assigns the largest membership degrees to slopes between 35° and 45° . Slopes flatter than 30° and steeper than 50° are assigned low membership degrees as avalanches become increasingly unlikely for such slopes.

2.2 *Wind shelter index*

The literature clearly reports the importance of wind - terrain interaction for avalanche release estimation. Many studies (e.g. Maggioni and Gruber, 2003; Vontobel, 2011) have found concave areas to be more prone for avalanche release. One possible reason is that snow under wind influence is mostly deposited in leeward slopes or gullies or behind downslope terrain steepenings. Existing algorithms take into account these effects by using a curvature measure. On the other hand, studies for snow hydrological purposes demonstrated the good performance of terrain based wind-shelter parameters to reproduce patterns of snow accumulation to a remarkable well extent (Schirmer et al., 2011; Winstral et al., 2002). The use of a wind shelter parameter has, in our opinion several advantages over a curvature measure:

- (1) A wind shelter parameter detects both, wind sheltering effects due to changes of planar and

profile curvature. Planar and profile curvature require normally two separate calculations.

(2) A wind shelter parameter calculates sheltering effects with respect to a given wind direction which is not possible using curvature. This enables the user for example to define release area scenarios taking into account the main wind direction for hazard mapping purposes or define release scenarios with regard to the different directions of potential storm events for more short term hazard mitigation measures.

In this study we use the wind shelter parameter of Plattner et al. (2006) which is a slightly modified version of the sheltering parameter of Winstral et al. (2002):

$$\text{Shelter index}(S) = \arctan\{\max\{z(x_0)-z(x)\}\}, \quad (2)$$

$|x_0-x| : x \text{ in } S$, where $S = S(x_0, a, \Delta a, d)$ is a subset of grid cells within a distance of Δd and a range of direction of $a \pm \Delta a$ from the central cell x_0 . In our implementation we replaced the “max” function by the 3rd quantile. This accounts for the fact that punctually very large sheltering effects might be outweighed in case that the surrounding area is open to wind influence (e.g. large rocks in an otherwise open slope). The wind shelter index varies between -1.5 and 1.5 for complex alpine terrain. Negative values correspond to wind exposed terrain, positive values to wind sheltered terrain. Therefore, the degree of membership $\mu(x)$ to the class PRA of wind shelter is modeled using a generalized bell membership function with the parameters $a=2$, $b=3$, $c=2$.

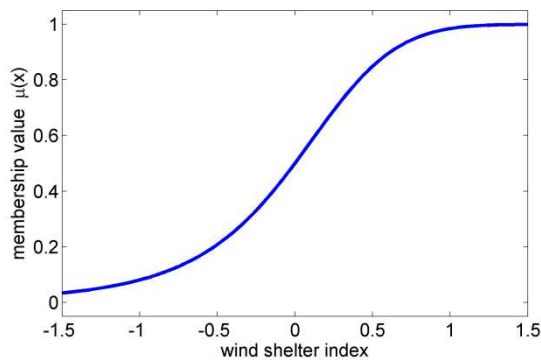


Fig. 2: Membership function for wind shelter index

2.3 Snow depth dependent roughness parameter

The third terrain parameter chosen is roughness. The role of this parameter is to integrate microtopography together with its alteration under snow influence into release area definition.

We use the roughness measure of Sappington et al. (2007) which calculates roughness within a 3x3 kernel window around every grid cell by taking into account changes of slope and aspect. Depending on the scale chosen for slope and aspect (Wood, 1996), a scale dependent roughness measure can be derived.

In previous work (Veitinger et al., 2014), we showed that the scale where terrain smoothing processes are active is related to snow depth and its variability. We therefore aimed to identify the optimal scale of a summer terrain to approximate a given snow situation in a winter terrain. For this purpose we correlated multi-scale summer terrain roughness with winter terrain roughness derived from high resolution LIDAR snow depth measurements performed by airborne laser scanning.

Fig. 3 thus shows the relation between summer and winter terrain roughness in a high alpine slope of complex terrain and a mean slope of 35°. The scale of maximum correlation increases with increasing snow depth and its variability.

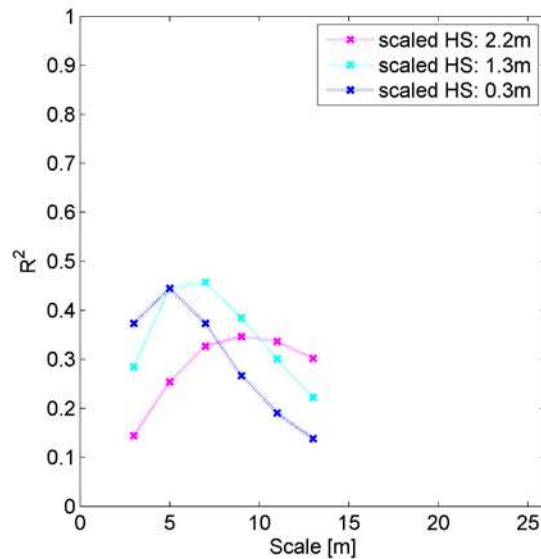


Fig. 3: Example of correlation of multi-scale terrain roughness with winter terrain roughness. Mean snow depth in the slope was multiplied by its standard deviation to account for the degree of variability influencing the smoothing effect.

This relationship is used to adjust the roughness parameter as a function of a given snow depth.

We further distinguish between concave terrain roughness (e.g. gullies) where snow accumulates and convex terrain features such as rocks or

ridges using a local wind shelter index. This index assigns positive roughness values for wind exposed features and negative roughness for wind sheltered roughness features representing potential accumulation zones of snow.

The degree of membership $\mu(x)$ to the class PRA of roughness is modeled using a generalized bell membership function with the parameters $a = 0.01$, $b = 3$, $c = -0.009$ (Fig. 4).

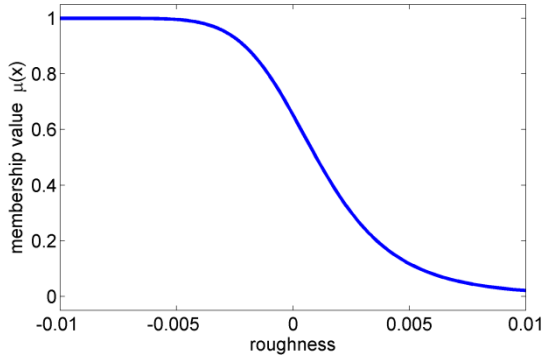


Fig. 4: Membership function for roughness

According to roughness values found in avalanche experiments and by expert interpretation, the roughness membership function assigns high membership degrees for concave and planar terrain features. Membership values strongly decrease for roughness between 0 and 0.005. Between 0.005 and 0.01, roughness values are assigned low membership degrees accounting for the fact that avalanches are unlikely to happen but are possible in unfavorable conditions. Above 0.01, avalanches are not considered to happen anymore.

2.4 Fuzzy operator

To define the membership degree to the class “potential release area (PRA)”, we apply the “fuzzy AND” operator as defined by Werners (1988). For the three fuzzy sets slope $\mu_s(x)$, roughness $\mu_r(x)$ and wind shelter $\mu_w(x)$, the degree of membership to the class PRA is defined by

$$\mu_{PRA}(x) = \gamma \min(\mu_s(x), \mu_w(x), \mu_r(x)) + \frac{(1-\gamma)(\mu_s(x) + \mu_w(x) + \mu_r(x))}{3} \quad (3)$$

With γ defined as:

$$\gamma = \min(\mu_s(x), \mu_w(x), \mu_r(x)) \quad (4)$$

Depending on the value of γ , the operator varies between the minimum and the average of the three fuzzy sets. γ is function of the smallest membership value of the three fuzzy sets. The smaller the minimum value, the more the operator tends towards the minimum operator. The larger the minimum value, the more the operator resembles an averaging operator. The behavior of this operator and in particular the role of γ can be best illustrated using an example. Let us imagine a medium steep slope of 32° with $\mu_s(x) = 0.5$ which is situated in medium rough terrain ($\mu_r(x) = 0.5$) and once in complete smooth terrain ($\mu_r(x) = 0.8$). If we use the classic minimum operator, both slopes would obtain the same membership value to the class PRA, although by our own judgment, we would assume a generally higher release probability for the smooth slope. In contrast, our operator would assign a higher membership value to the smooth slope than to the rough slope as $\gamma = 0.5$ allows compensation from the larger roughness membership value.

Assuming now the same two slopes show a gradient of 28° instead of 32° , resulting in $\mu_s(x) = 0.08$ and $\gamma = 0.92$. A membership value to the class PRA close to 0.1 (0.13 and 0.11 respectively) would be assigned to both slopes. Due to the small γ value, the operator corresponds in this case almost to the minimum operator allowing for almost no compensation for the low slope value. This behavior is in our opinion also reasonable as a 28° slope produces an avalanche only in very rare cases even when the slope would be perfectly smooth.

3. RELEASE ALGORITHM DESIGN

3.1 Input, output and software

The algorithm is programmed in the free software programming language R (version 3.0.3, <http://www.r-project.org>). In particular the “RSA-GA” package (Brenning, 2008), providing access to the geocomputing and terrain analysis functions of the open source desktop GIS, SAGA (<http://www.saga-gis.org>), was used. Further, a Python (<https://www.python.org/>) interface was implemented to run the script as a tool in ESRI ArcGIS (ArcGIS 10.2 for Desktop).

To perform a calculation of release areas, three mandatory inputs have to be provided: A digital elevation model (DEM), a main wind direction and a mean snow depth in the area. Optionally, a forest mask can be provided to exclude forested areas from potential release areas.

The development of this algorithm and its corresponding window sizes and scales are based on a relatively high DEM resolution of 2m to allow calculations of early winter scenarios with very little snow depth where small scale terrain features are relevant. If only coarser DEMs are available, resampling to a 2m resolution is recommended. One still has to keep in mind that calculation of early winter situations may not be very meaningful for scales smaller than the initial DEM resolution as small scale terrain features are not captured by the initially coarse DEM resolution.

Further a mean wind direction must be provided. By default a direction of 0° with a tolerance of 180° is set. This setting should be used if release area definition independent of a specific wind direction should be performed. Still, this setting gives higher possibility to wind sheltered areas such as gullies being potential release area. If a specific wind direction should be used (e.g. to simulate potential release areas due to a storm event from a certain direction) the wind direction can be set. As local winds often strongly deviate from the main wind direction, it is recommended to allow a certain tolerance from the main wind direction of at least $\pm 30^\circ$. In case that the local wind regime is known, it can already be taken into account in the input parameters.

The third input consists of an estimated snow depth in the area under examination. The algorithm uses the input snow depth to associate it with the corresponding scale for the calculation. Further it is required to provide the degree of terrain smoothing. Two options exist, a regular degree of terrain smoothing (default) and low terrain smoothing. The latter should only be used for situations where significant snow distribution did not (yet) occurred (e.g. first snowfalls in early season under little wind influence. In all other cases the default setting should be chosen.

The output provides four possibility classes for a slope to be potential release area:

$\mu_{PRA} < 0.25$: low possibility for PRA.

$0.25 < \mu_{PRA} < 0.5$: medium - low possibility for PRA.

$0.5 < \mu_{PRA} < 0.75$: medium - high possibility for PRA.

$\mu_{PRA} > 0.75$: high possibility for PRA.

3.2 *Schema of algorithm*

The different steps that are executed in the model are as follows:

- (1) Determination of a characteristic scale as a function of snow depth and the degree of terrain smoothing.
- (2) Calculation of roughness at the characteristic scale.
- (3) Calculation of slope at a 10m scale.
- (4) Calculation of wind shelter parameter as a function of input wind direction and tolerance at the characteristic scale.
- (5) Calculation of degree of membership to the class PRA for every raster cell using the fuzzy operator.
- (6) Exclusion of forested areas from the class PRA.
- (7) Exclusion of potential PRAs $< 500\text{m}^2$ from the class PRA.
- (8) Rendering the fuzzy output of the class PRA in four possibility classes.

4. EXAMPLE

The following example is taken from current avalanche mitigation practice in Switzerland. It is a mountain road situated in the canton Uri, in the center of Switzerland close to the Gotthard pass. The mountain road has NE-SW orientation and is threatened by the different avalanche paths of the "Böschchen avalanche". The avalanche path is NW oriented and characterized by a lower release area zone and higher alpine avalanche zone separated by a flatter terrace in between. The lower release zone is covered with low bushes and characterized by many small gullies which produce the majority of avalanches. The whole lower release zone is steeper than 30° , meaning that avalanches may occur everywhere. Due to its proximity to the main Alpine ridge, the slope is exposed to storm events from NW direction as well as Foehn situations from S direction often in combination with significant snowfalls. Generally, the S to SW storm events are more critical situations responsible for the majority of avalanche events hitting the road.

We analyze one typical avalanche period and apply the algorithm to the according wind and snow situation obtained from a nearby weather station at the time of avalanche release. On February 2, 2014, after a significant snowfall of around 40 cm, 11 small avalanches, naturally released in the lower avalanche release zone (Fig. 5), hit the road. Snow depth in the area after the snowfall was 120 cm. Wind influence was rather low.

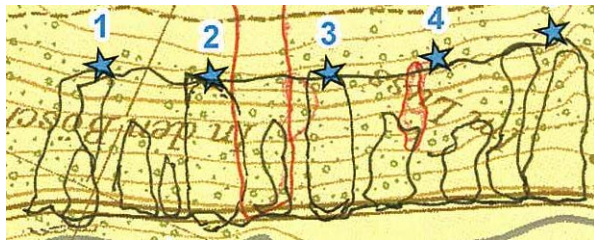


Fig. 5: Observed avalanches on February 2, 2014, as mapped from local avalanche service.

Fig. 6 shows the result of a release area simulation with an input snow depth of 1.2 m and no main wind direction for the same area than shown in Fig. 5. We observe that the small channels in the lower release area are well detected and assigned mostly high possibility (red color) being release area. This is in good agreement with the observed avalanches which mostly released in the small gullies. Further the algorithm indicates several areas with medium - low and low possibility (yellow and light green color) for some area in between the gullies indicating that large, continuous avalanche releases are rather not to expect under this snow scenario.

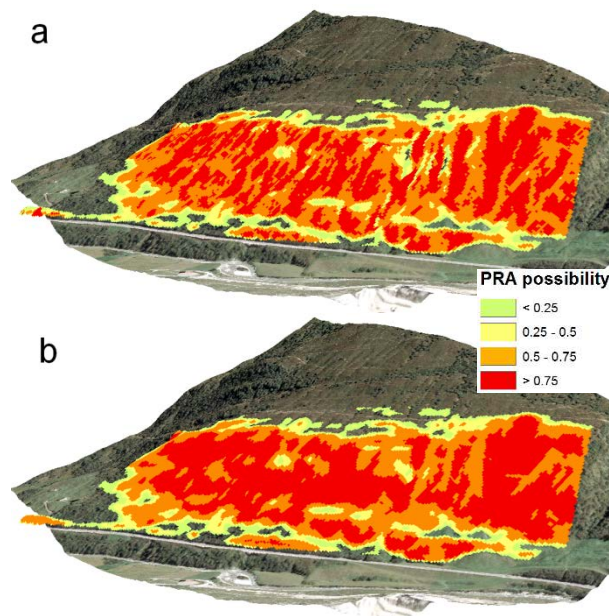


Fig. 6: PRA possibility for a snow depth of (a) 1.2 m and (b) 2.5 m. No specific wind direction is set.

If we assume a snow depth of 2.5 m instead of 1.2 m, the result would be a more continuous area of high possibility, indicating that under this scenario, larger release areas can potentially occur. Main wind directions from SE to SW direction (not

shown here), produce similar release area patterns as shown in Fig. 6a, indicating that those wind directions are the most critical for this slope.

Further, we calculated scenarios for a W wind direction and a NW wind direction with a snow depth of 1.2 m (Fig. 7). We observe that for the NW scenario, the algorithm assigns low to medium - low possibility for the whole area. Due to the fact that the release area is completely wind exposed, the possibility of avalanche formation under these conditions is strongly reduced. For a W direction, we observe that especially the deeper gullies and the more N oriented slopes are assigned medium - high possibility being release area. This reflects well the cross loading conditions which are often observed under this wind direction also leading to avalanching.

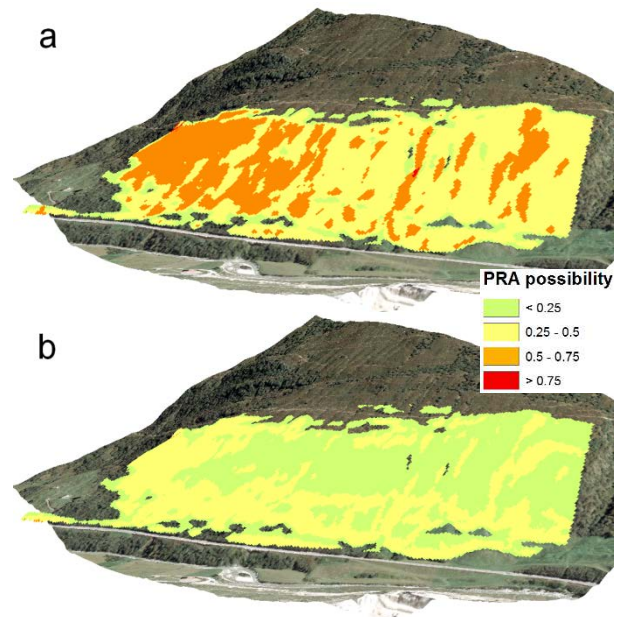


Fig. 7: PRA possibility for (a) a W wind direction and (b) a NW wind direction. Snow depth is set to 1.2 m.

5. CONCLUSIONS

The presented release area tool showed several improvements over existing release area procedures.

- The algorithm detects small scale terrain features allowing the partitioning of the whole potential release in adequate sub basins.
- Terrain roughness is adjusted as a function of snow distribution allowing assessing the influence of terrain smoothing on potential release area size and location.

- It is possible to define release area scenarios as a function of a main wind direction.

However, this approach has also its limitations.

- Statistical modelling of terrain smoothing only captures smoothing effect of snow distribution. Drift features such as dunes or cornices cannot be modeled.
- Local variability of terrain smoothing as for example due to varying local wind directions (or speeds) from main wind direction or large scale sheltering from neighboring mountain ridges is not captured.
- Potential size of avalanche release areas, especially in a given situation, depend strongly on snowpack (stability) and meteorological conditions (e.g. temperature) which are not taken into account by the algorithm.

Despite these limitations, the tool can be a valuable help for hazard mapping engineers as it facilitates the partitioning of release areas as well as the definition of design events. We believe that it might further be useful as a planning instrument for road and ski resort safety. Future improvements of the algorithm, as for example linking the different degrees of PRA membership with snow conditions in the avalanche path would further increase the potential applicability in short term hazard assessment.

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